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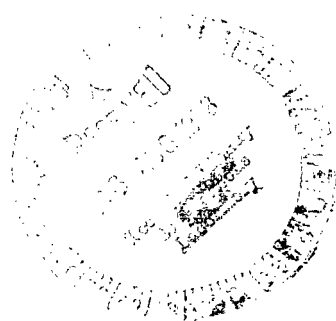


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LEADING-EDGE-SUCTION ANALOGY
OF VORTEX LIFT TO THE DRAG DUE TO
LIFT OF SHARP-EDGE DELTA WINGS

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SUMMARY

A study has been made of the application of the leading-edge-suction analogy of vortex lift to the prediction of the drag due to lift of thin sharp-edge delta wings in incompressible flow. The study included comparisons with experimental results over a range of aspect ratios from 0.25 to 2.0. The results indicated that the drag due to lift can be predicted accurately by the zero-leading-edge-suction assumption, provided the vortex lift is accounted for by the leading-edge-suction-analogy method of NASA Technical Note D-3767. It was also found that because of the vortex lift, the drag due to lift for wings of extremely low aspect ratio can be less than that for optimum potential flow.

INTRODUCTION

Theoretical predictions of the aerodynamic performance of slender sharp-edge delta wings require consideration of nonpotential-flow effects in the form of leading-edge spiral vortices produced by leading-edge separation. These vortices have large effects on the performance characteristics, especially during take-off and landing, and accurate predictions of these effects are desirable. Theoretical approaches in the past have been based on various mathematical models of the spiral vortices (see refs. 1 to 5, for example) and have not provided sufficient accuracy because of the difficulty in calculating the size, shape, position, and strength of the primary and secondary spiral vortices and their feeding sheets. A new approach, which circumvents these problems, has been developed in reference 6. This approach relates the flow about the spiral vortices to the potential flow about the leading edge and formulates an analogy between the potential-flow leading-edge suction and the additional normal force which is induced by the vortex flow and from which the vortex lift can be determined. Comparisons of lift calculated according to this theory with experimentally determined lift at low speeds for sharp-edge delta wings covering a wide range of aspect ratios and angles of attack have indicated excellent agreement. (See ref. 6.) In view of the promising nature of the leading-edge-suction analogy,

the purpose of this paper is to investigate the application of this analogy to drag due to lift of sharp-edge delta wings.

SYMBOLS

A	wing aspect ratio, b^2/S
b	wing span, meters
ΔC_D	drag coefficient due to lift
C_{Di}	potential-flow induced drag
C_L	total lift coefficient, $C_{L,p} + C_{L,v}$
$C_{L,p}$	lift coefficient determined by linearized potential-flow theory (present application does not include leading-edge suction component)
$C_{L,v}$	lift coefficient associated with leading-edge separation vortex
C_S	leading-edge suction coefficient (in plane of wing and perpendicular to leading edge)
C_T	leading-edge thrust coefficient (in plane of wing and parallel to flight direction)
K_p	constant of proportionality in potential-flow lift equation
K_v	constant of proportionality in vortex lift equation
M	Mach number
S	wing area, square meters
α	angle of attack, degrees
Λ	leading-edge sweep angle, degrees

DISCUSSION AND RESULTS

Theoretical Approach

Lift.- The method employing the leading-edge-suction analogy for predicting the vortex lift of sharp-edge delta wings is described in reference 6, where a comparison of the predicted lift with experimental results is also presented. Briefly, this method starts with the assumption, substantiated by experiment, that over the normal angle-of-attack range, the flow external to the vortex passes around the vortex and reattaches to the wing upper surface. (See fig. 1.) It is then assumed that the total lift is comprised of two parts: (1) a lift associated with the reattached flow which can be estimated by an appropriate application of potential-flow lifting-surface theory, and (2) a vortex lift which is equal to the force required to maintain the equilibrium of the potential-type flow around the spiral vortex.

The potential-flow lift term is shown in reference 6 to be given by

$$C_{L,p} = K_p \sin \alpha \cos^2 \alpha \quad (1)$$

where K_p is the lift-curve slope given by small-angle-of-attack potential-flow lifting-surface theory, $\sin \alpha$ accounts for the true boundary condition, and $\cos^2 \alpha$ arises from the assumption of a Kutta-type flow condition at the leading edge.

To determine the vortex lift, the method of reference 6 suggests an analogy between the force required to maintain the flow about the spiral vortex and that required to maintain potential flow about the leading edge as illustrated in figure 2. For the potential flow, the force is the well-known leading-edge suction which has been shown to be relatively independent of leading-edge radius, the lower angle-of-attack-induced velocities associated with the larger radius acting over a larger area to provide the same suction force as for the smaller radius. With leading-edge vortex flow, a Kutta-type condition exists at the leading edge and the leading-edge suction is lost. However, the flow around the vortex is somewhat analogous to the potential flow around the large leading-edge radius. The primary difference is that the equilibrium force must now be supported by the wing upper surface rather than by the leading edge and therefore, the leading-edge suction is converted to a normal force. The vortex lift term, based on this approach, is given in reference 6 to be

$$C_{L,v} = K_v \sin^2 \alpha \cos \alpha \quad (2)$$

where $K_v \sin^2 \alpha$ gives the potential-flow leading-edge suction and therefore the vortex normal force, and $\cos \alpha$ gives the component in the lift direction.

By combining equations (1) and (2), the total lift coefficient is given by

$$C_L = K_p \sin \alpha \cos^2 \alpha + K_v \cos \alpha \sin^2 \alpha \quad (3)$$

For convenience, the variations of K_p and K_v , as obtained from reference 6, are reproduced in figure 3.

Drag due to lift.- For the thin flat sharp-edge wings having fully developed vortex flow which is of interest in this paper, it is reasonable to assume that a Kutta-type flow exists along the leading edge and that the resultant force associated with angle of attack is therefore directed normal to the wing-chord plane. With this assumption and the assumption that the effects of angle of attack on skin friction are small, the drag coefficient due to lift can be given by

$$\Delta C_D = C_L \tan \alpha \quad (4)$$

or with the aid of equation (3),

$$\Delta C_D = K_p \sin^2 \alpha \cos \alpha + K_v \sin^3 \alpha \quad (5)$$

where K_p and K_v are obtained from figure 3.

It is normally desired to analyze drag due to lift in terms of lift coefficient rather than angle of attack. Because of the trigonometric terms involved, it is easiest to compute the lift coefficient for various angles of attack by using equation (3) and then to substitute in equation (4) in order to obtain the drag for a given lift coefficient.

In this paper, previously determined experimental drag due to lift of sharp-edge delta wings is compared with the theoretical results based on the leading-edge-suction analogy for vortex lift, and in addition, the theoretical values obtained by two other assumed flow conditions are presented for comparison. The three assumed flow conditions and the resulting equations are as follows:

(1) Zero leading-edge suction with vortex lift

$$\Delta C_D = C_L \tan \alpha$$

where

$$C_L = K_p \sin \alpha \cos^2 \alpha + K_v \cos \alpha \sin^2 \alpha \quad (6)$$

(2) Zero leading-edge suction with no vortex lift

$$\Delta C_D = C_L \tan \alpha \quad (7)$$

where

$$C_L = K_p \sin \alpha \cos^2 \alpha \quad (8)$$

(3) Full leading-edge suction (potential flow)

$$\Delta C_D = C_{Di} \quad \text{(Induced drag according to ref. 7)} \quad (9)$$

The second assumption is considered unrealistic, since it would appear that for the wings under consideration, some vortex lift always accompanies a loss of leading-edge suction. It is presented, however, for comparison purposes inasmuch as it has been utilized quite often in the past.

Comparison With Experiment

Calculations based on the previously described assumptions are compared with experimental¹ results in figure 4, where the drag coefficient due to lift is presented as a function of the lift coefficient squared. The results indicate, in general, excellent agreement between experiment and the theory based on the zero-leading-edge-suction assumption with vortex lift included by the method of reference 6. The one exception indicated is for $A = 0.25$, where the measured drag is somewhat higher than the theoretical drag. This exception is believed to be due to a breakdown in the analogy caused by a strong mutual interference of the two vortices on this extremely narrow wing. For the sharp-edge slender wings studied, the experimental drag due to lift is always less than that from calculations based on the assumption of zero leading-edge suction with no vortex lift. It must be kept in mind that this reduction does not indicate the attainment of leading-edge suction, but reflects the benefit of a reduced angle of attack (for a given lift coefficient) made possible by the vortex lift associated with leading-edge separation. From this result, it is apparent (as pointed out in ref. 12) that the potential improvement offered by camber and twist can be considerably less than that implied by theories which neglect the vortex lift. The drag due to lift calculated by the full-leading-edge-suction (potential-flow) condition of reference 7 is, in general, lower than the experimental results, and thereby indicates there is some benefit to be obtained by maintaining the leading-edge suction through the use of leading-edge radius or an equivalent suction by use of camber and twist. However, it is noted that as the aspect ratio is reduced, both the experimental values and those predicted by the vortex-lift theory approach those given by the full-leading-edge-suction theory. In fact, for $A = 0.25$, the drag due to lift for the zero-leading-edge suction theory (with vortex lift) is actually less than that predicted by planar-wake theory for full leading-edge suction.

The reduction in drag below the potential-flow values for low aspect ratios was predicted in reference 12 by use of a rough estimate of the vortex lift. It was also pointed out in reference 12 that camber and twist calculations for sharp-edge slender wings should take into account the vortex-lift effects if optimum performance is to be obtained. A rather extreme example of this fact can be seen in the results for the wing having an

¹The data for the wing with aspect ratio $A = 0.25$ were recently obtained by Messrs. J. E. Lamar and W. P. Phillips of the Langley Research Center. The data for the other wings were obtained from references 8 to 11.

aspect ratio of 0.25 shown in figure 4. It should be noted that over the entire lift coefficient range, the use of camber and twist to regain the effect of the full leading-edge thrust (by a distribution along the chord) might actually result in an increase in the drag rather than a decrease. This rather unusual situation can possibly be explained with the aid of the leading-edge-suction analogy of vortex lift, as shown in figure 5, where the relationship between potential-flow leading-edge suction and thrust is illustrated for a moderate- and low-aspect-ratio delta wing. For the wing of moderate aspect ratio, it can be seen that a sizable thrust component of the suction force is available in potential flow and therefore, camber and twist would be desirable. However, for the low-aspect-ratio wing having an extremely high leading-edge sweep angle, it can be seen that only a small thrust component is developed and, as shown by the results of figure 4, it appears better to allow the flow to separate and convert the suction to vortex lift. The resulting reduction in angle of attack required for a given lift coefficient reduces the drag more than the leading-edge thrust would have reduced it.

These effects are illustrated further in figure 6, where the experimental values of drag coefficient for a lift coefficient of 0.50 are presented as a function of aspect ratio. Also shown are the theoretical results based on the three assumptions discussed previously. From this figure, it can be seen that for aspect ratios below about 0.4, the drag is lower for zero-suction theory (with vortex lift) than for potential-flow theory. It must be recognized, however, that the potential-flow theory is for a wake system in the extended chord plane and that for the high angles of attack encountered with slender wings, the deviation of the wake from the extended chord plane may alter the potential-flow drag.

The aspect ratio at which the separated and attached flow result in the same drag due to lift is a function of lift coefficient. (See fig. 4.) The combinations of aspect ratio and lift coefficient for which the leading-edge separation flow provides lower drag due to lift than the potential-flow theory ($\Delta C_D = C_L^2 / \pi A$) are presented in figure 7. In the upper left area, the ability of camber and twist to reduce drag due to lift of sharp-edge wings is somewhat questionable.

It becomes rather apparent from these considerations that the vortex-lift effects must also be considered for the "off-design" lift coefficients associated with take-off and landing of wings cambered and twisted for supersonic cruise. In addition, the possibility exists that drag reductions might be achieved by designing the cambered and twisted wing in such a manner that some vortex lift occurs at the design lift and that this vortex lift also provides a thrust component due to the inclination imposed by the cambered leading edge.

CONCLUSIONS

A study of experimental and theoretical results on the drag due to lift of slender sharp-edge delta wings has indicated the following:

1. The drag due to lift can be predicted accurately with the zero-leading-edge-suction assumption, provided the vortex lift is properly taken into account. The leading-edge-suction-analogy method of NASA Technical Note D-3767 appears to provide a satisfactory method for determining the vortex lift.

2. In the extremely low range of aspect ratios, the effect of vortex lift on the angle of attack required for a given lift coefficient is sufficient to offset the loss of leading-edge thrust, and the drag due to lift with leading-edge separation is lower than that for optimum potential flow for a rather large lift range.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., May 17, 1968,
126-13-01-50-23.

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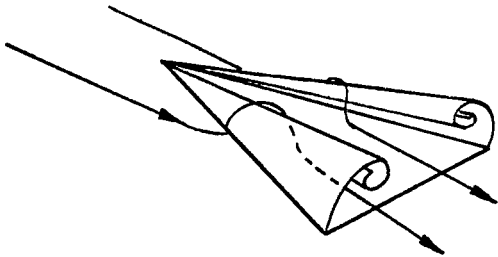


Figure 1.- Leading-edge spiral vortices and reattached flow around them.

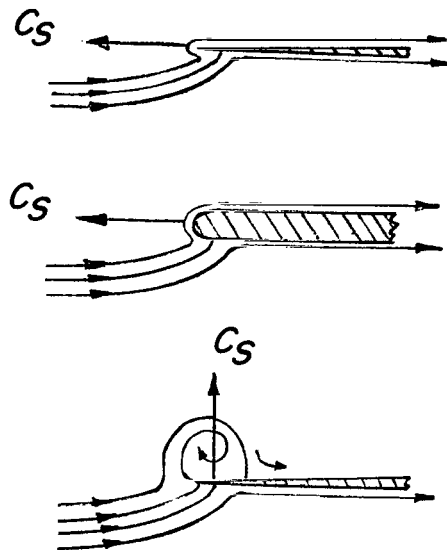


Figure 2.- Leading-edge-suction analogy of reference 6.

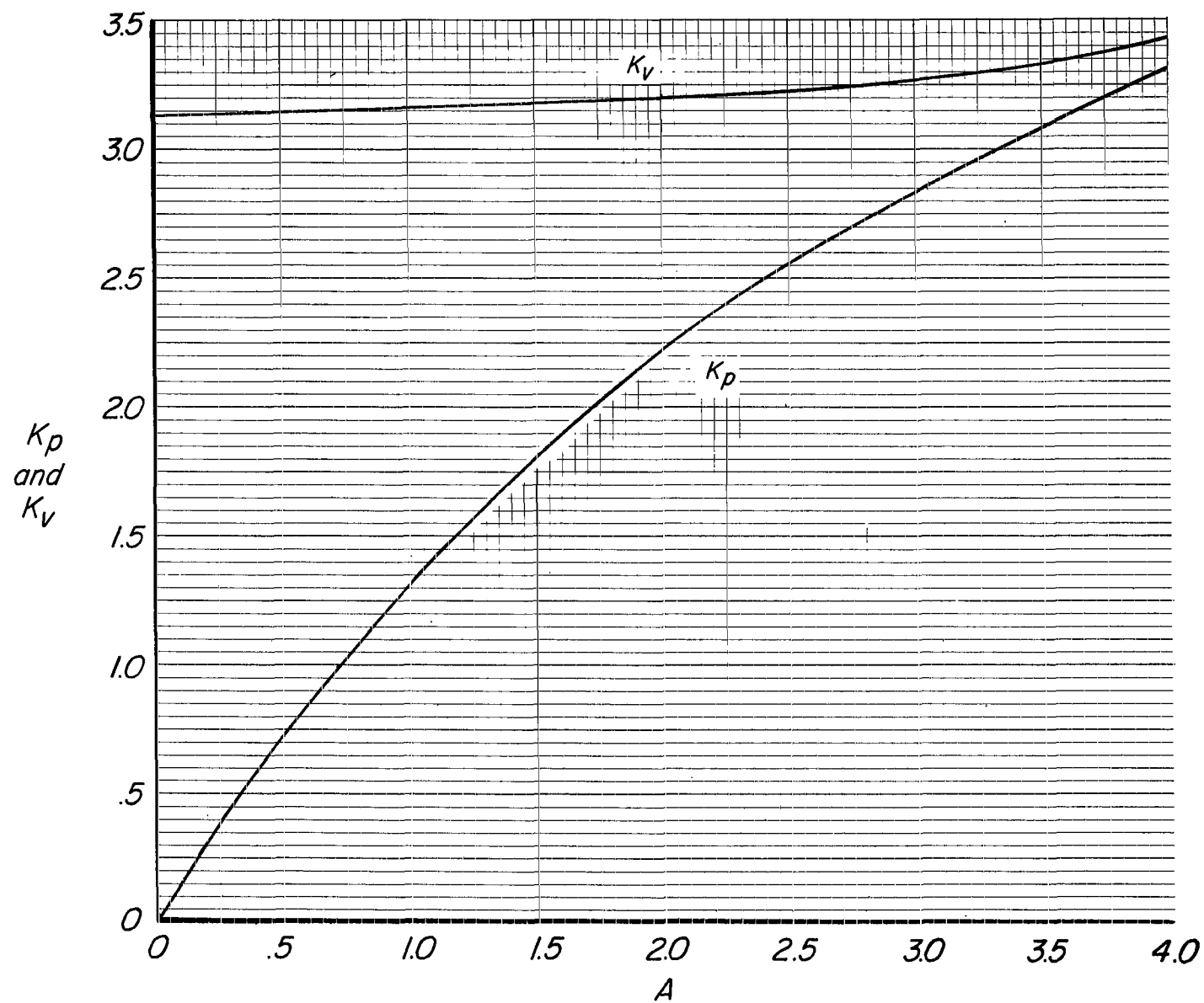


Figure 3.- Variations of K_p and K_v for delta wings. $M \approx 0$.

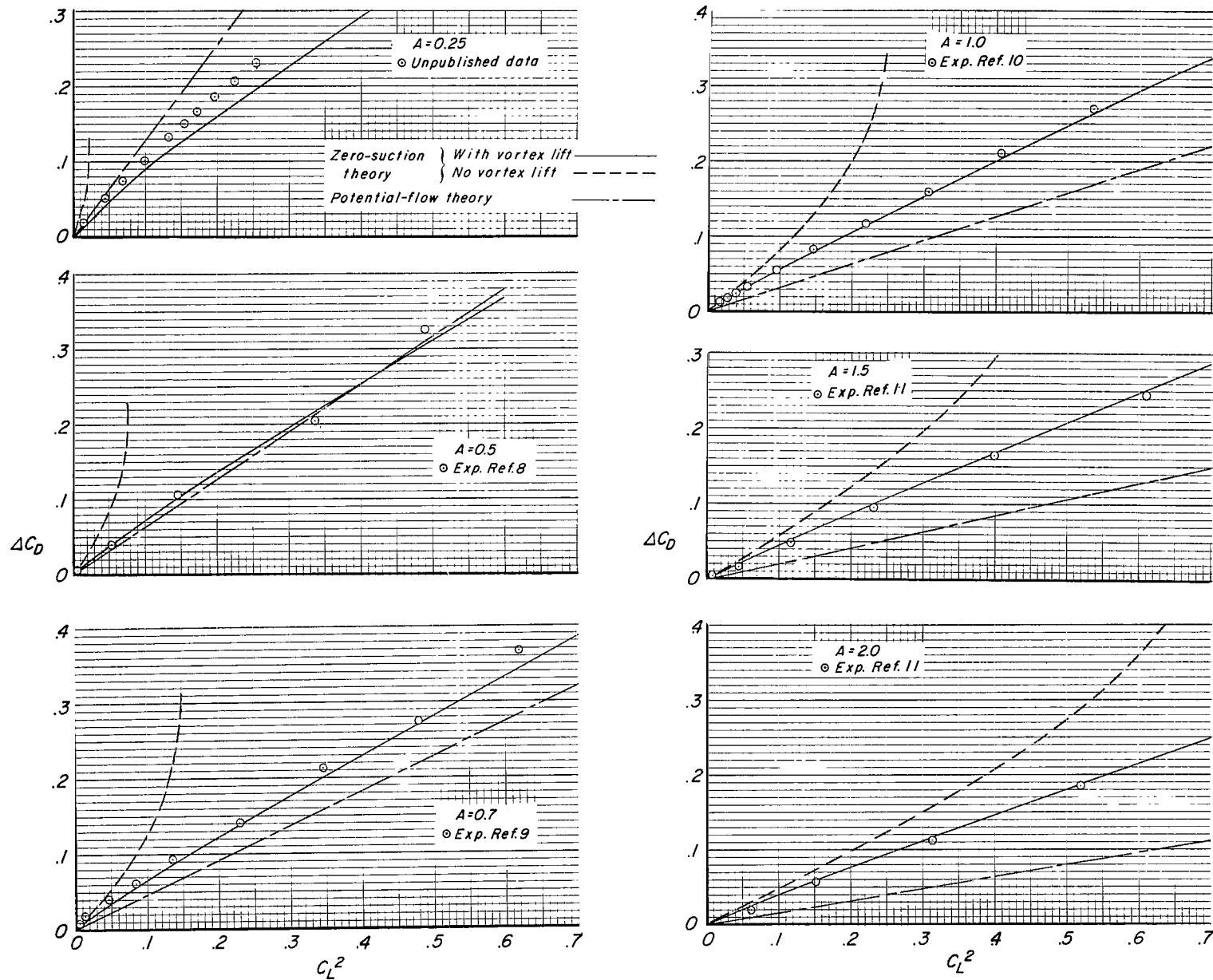


Figure 4.- Comparison of experimental drag due to lift with the results of the three theoretical methods studied. $M \approx 0$. Circular symbols represent experimental data.

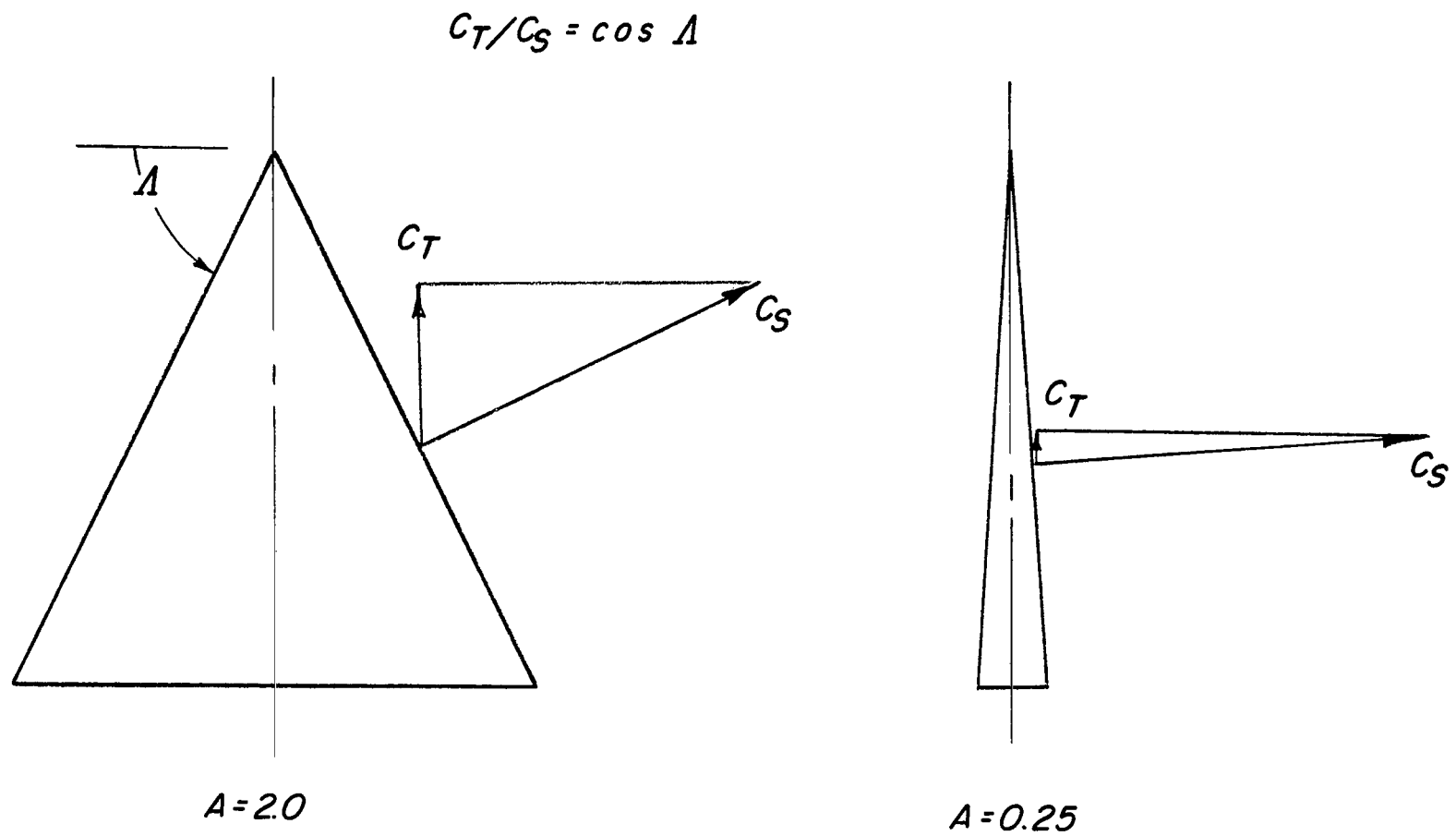


Figure 5.- Relationship between potential-flow leading-edge suction and thrust.

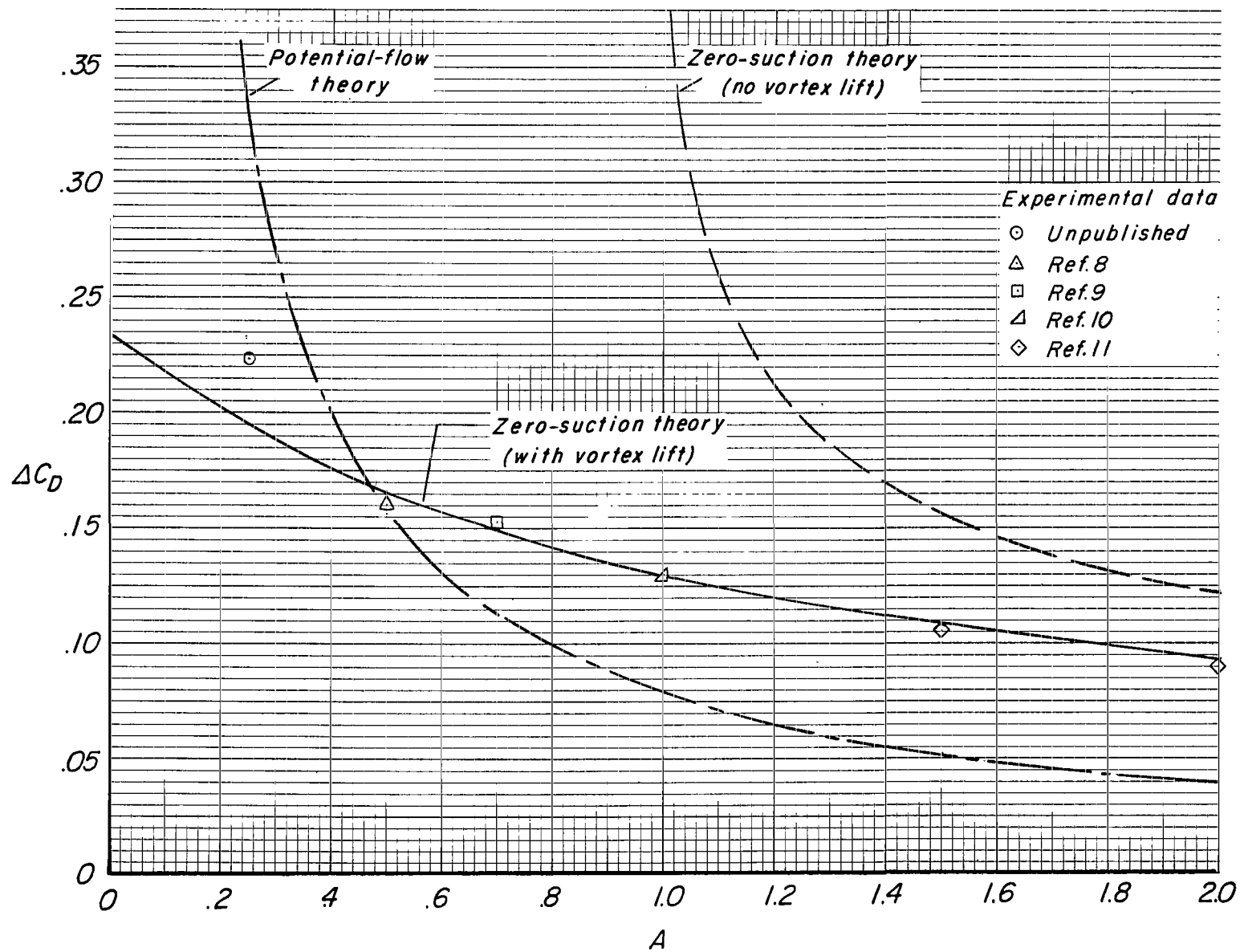


Figure 6.- Comparison of experiment and theory. $C_L = 0.50$; $M \approx 0$.

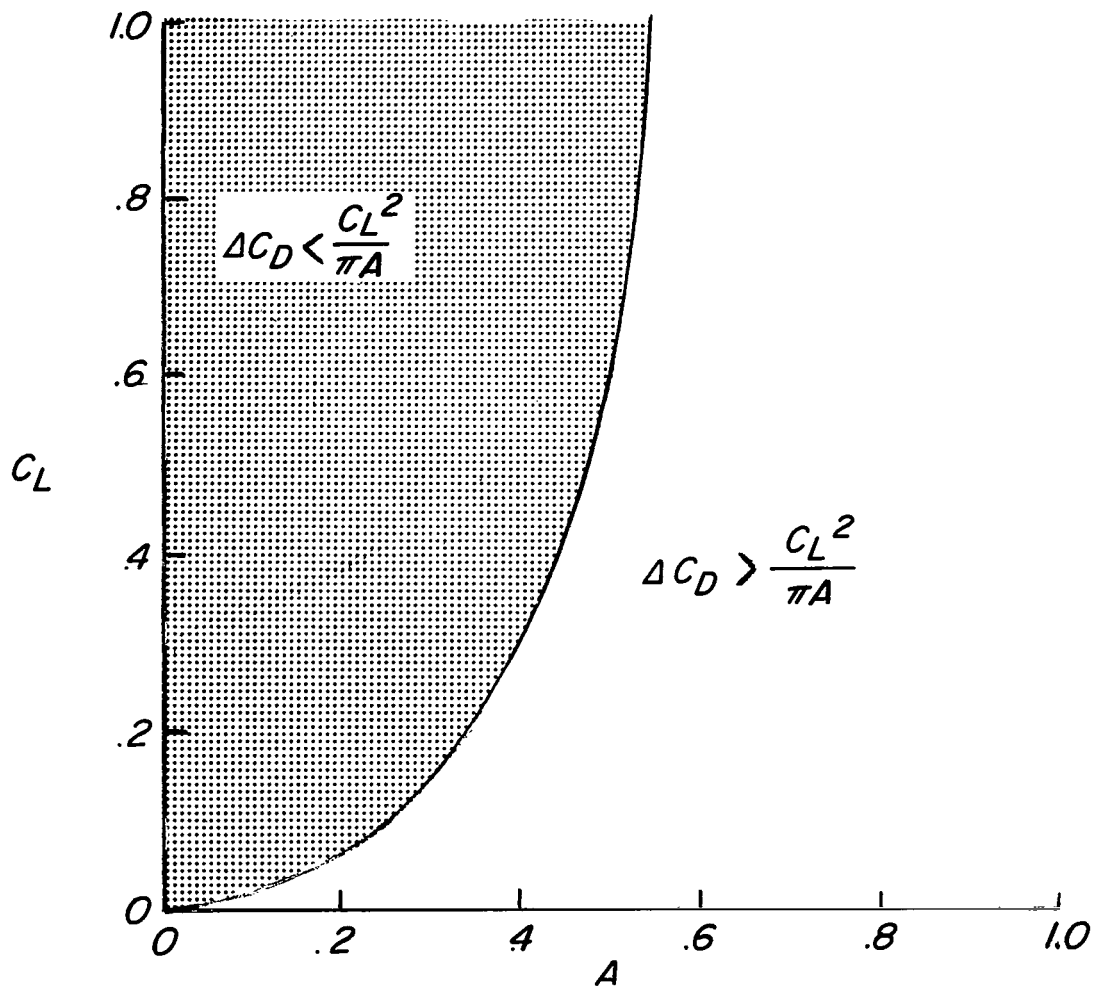


Figure 7.- Drag-due-to-lift boundary for sharp-edge delta wings. $M \approx 0$.

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